Parametric CAD Modeling: New Principles for Robust Sketch Constraints

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Abstract. Automated Finite Element Analysis (FEA) requires sketches to cope effortlessly with dimensional changes to assess functional robustness. However, sketch robustness is often neglected and overlooked in today's design processes and causes a waste of resources throughout the product development. The present study explores how CAD sketches are made less prone to regeneration failure when the dimensions in the sketch vary as much as $\pm 80\%$. Three new Robust Sketch Principles (RSPs) to improve sketch robustness are developed based on commonly experienced failure modes. The first part of the study assesses the new RSPs' impact by engaging nine M.Sc. engineering graduate students and five industrial CAD specialists in a comparative study. The participants are asked to constrain an existing sketch with and without knowledge of the new RSPs. The study shows that the initial practice of the participants leads to poor sketch robustness, while less than 30 minutes of training with RSPs enable all participants to achieve a statistically significant improvement in sketch robustness. The second part of the study explores the industrial application of the RSPs by redrawing existing product sketches and comparing the robustness with and without the new RSPs. Both parts of the study demonstrate that the RSPs improve robustness significantly and widen the parameter space for automated FEA simulations.

Keywords: Automation, CAE, FEA, DOE, guidelines, error reduction
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1 INTRODUCTION

The backbone of modern mechanical design projects is 3D feature-based CAD models [29, 25]. Traditionally, the primary need to change a CAD model has been design-related, resulting in manual changes to configurations, features, or individual dimensions based on new insights and design requirements. However, advances in state-of-the-art Computer-Aided Engineering (CAE) techniques have increased the need for analysis-related

CAD model changes. For example, when (i) analyzing the probabilistic performance within the allowable dimensional tolerance range [11], (ii) exploring a more extensive solution space, or (iii) performing parametric optimization [22]. In all cases, it is advantageous to have a robust CAD model that facilitates unlimited parametric changes without model regeneration failures. "Parametric modeling," a history-based, feature-based approach, is commonly used to create CAD models. The parametric controls are critical for sensitivity studies because they allow for precise geometry adjustment enabling evaluation of the functional impact. The newer approach, "Direct modeling," on the other hand, is a history-free, parameter-free approach that does not keep a change log of features and is thus inapplicable for sensitivity studies. However, due to the lack of a structured methodology, the flexibility and robustness of CAD models strongly depend on the expertise and focus of the engineer [30, 5]. While some industrial guidelines exist, these are often protected to maintain the competitive advantage [3], and most CAD training courses focus on specific software tools rather than on best practices to construct flexible and robust CAD [6].

The lack of flexible and robust CAD models has severe consequences in product development, as it limits the uptake of Robust Design Methodology [16], the utilization of FEA-based variation simulation [27, 28], and Multidisciplinary Design Optimization (MDO) [20]. A roadmap for estimating the cost of poor CAD quality is provided by Camba et al. [10]. While a direct cost estimate is not provided, the magnitude of the problem is underlined, which is further supported by Aranburu et al. [4], who emphasize the importance of robust CAD models. Branoff [8] and Bodein et al. [6] point out that achieving flexible and robust CAD is inefficient without applying a formal modeling strategy from the initiation of the CAD model. The claim is supported by Camba et al. [9] in a comparative study, including the three commonly known formal CAD strategies for solid feature modeling: (i) Delphi's Horizontal modeling [21], (ii) Explicit Reference modeling [6], and (iii) Resilient modeling [15]. In addition, Camba et al. [9] conclude their study by showing that Resilient modeling achieves the highest effectiveness in terms of CAD feature robustness and alteration time. While the existing formal strategies notably improve flexibility and robustness compared to completely lacking a strategy, the topic of applied dimensional variation and robust constraints in sketches is neglected [4]. The above-stated modeling strategies primarily focus on the feature tree structure to enforce robust relationships between Parent-Child features.

Different sketch-related failure modes can occur when regenerating the CAD model depending on the scale of the applied variation and how the sketch is constrained [17]. However, the typical consequence of a regeneration failure is manual interference with the CAD model, an invalid strategy for comprehensive Finite Element Analysis (FEA)-based variation simulation used, e.g., to assess design and parameter sensitivities. In brief, FEA-based variation simulation involves generating several CAD variants of a given design determined by a Design of Experiment (DOE) and running a FEA on each. The number of variants depends on the number of investigated parameters but, based on experience, it is typically in the range of 8-256 for a sensitivity analysis. Thus, understanding and avoiding regeneration failures is fundamental to increasing the uptake of advanced simulation processes. While the open literature provide some guidelines for producing quality CAD models [12], no directly applicable principles on how to apply sketch constraints that maximize robustness are available. The magnitude of the problem is indicated in an industrial survey by Jackson and Buxton, where; "*57% agreed that model modification requires expert CAD knowledge, 48% experience that models are inflexible and fail after changes, and 40% find that only the original designer can change models successfully*" [19]. To solve the problem in an idealized design process where, e.g., Skeleton modeling [14] controls assembly constraints and Resilient modeling manages healthy feature to feature relations, a missing piece in the puzzle is effective sketch principles that avoid regenerations failures. Consequently, this paper aims to enhance the existing formal CAD strategies with new Robust Sketch Principles (RSPs). The present study introduces the new RSPs and explores how they can control dimensional sketch constraints and with minimal formal training of engineers to improve the robustness of complex CAD sketches. To test the effectiveness of the RSPs, a complex sketch was defined explicitly for the study. In feature-based parametric design, characterizing complexity has been attempted by several authors (see Camba et al. [9] for an overview). In general terms, the complexity can be categorized by *size*, *interconnectivity*, and *decomposition* [24]. Only *size*, defining the number of sketch constraints, is relevant for this study as *Interconnectivity* and *decomposition* relate to solid features. The first part of the present study consists of two assignments involving nine M.Sc. engineering graduate students and five industrial CAD specialists. The participants' task is to iso-constrain[1] a complex sketch requiring 16 dimensional constraints, first based on experience and secondly using the new RSPs. In the second part of the study, the industrial application of the RSPs is explored by applying the RSPs to three existing CAD sketches, all taken from marketed products[2], and the improved robustness is compared with the original dimensional sketch constraints. In both parts of the study, the robustness is tested and measured in a solution space with gradually increasing dimensional variation.

The effectiveness of the RSPs is statistically evaluated by the differences in robustness before and after application. The results show that sketch robustness is low even with a small amount of variation ($\pm 1\%$) when relying on current practice, even for experienced CAD designers. However, a statistically significant gain in robustness is observed when applying the new RSPs.

The paper is structured as follows; Section 2 defines the sketch failure modes and the robustness assessment. In section 3, the new Robust Sketch Principles are introduced. Section 4 outlines the methodology for evaluating the RSPs. In section 5, the obtained results of the improved sketch robustness are presented. Section 6 explores the industrial implications for unrobust sketches and the effects of the DOE type. Finally, section 7 summarizes the main conclusions of the study.

2 REGENERATION FAILURES AND ROBUSTNESS ASSESSMENT

The following section outlines: (i) A review of typical failures modes for sketch regeneration, and (ii) The definition for robustness assessment.

2.1 Failure Modes

Consider the simple sketch in Fig. 1, where a, b, c, and d are variable dimensions. Without a formal methodology, it is hard to imagine how much variation can be applied to these dimensions before the sketch has regeneration failures - an issue that becomes even more pronounced in complex sketches. Working with CAD and product design, the following three failure modes typically cause a sketch to fail.

2.1.1 Failure Mode 1 - Overlap

In commercial CAD software[3], a sketch has in most cases two critical requirements when used for solid modeling; (i) the sketch must have a closed profile, and (ii) only contain one positive area, assuming "thick feature" of lines is disregarded. Therefore, overlapping sketch lines, as seen in Fig. 2, will cause the related feature to fail as the software is unable to define one unique volume. Maintaining an overview of potential overlaps is possible when variation is applied in sketches with one or two variables. However, as the number of variables increases, which is likely for industrial case examples, the possible interactions can be extensive and unmanageable.

2.1.2 Failure Mode 2 - Invalid or Impossible Geometry

Good sketch practice recommends that a sketch is iso-constrained to ensure design consistency when the model is regenerated. Earlier work by Anderl and Mendgen [2] defined all sketch constraints as one category. However, commercial CAD software today splits sketch constraints into two types; dimensional (lengths, angles, and

[1] Also known as fully constrained
[2] Dimensions are changed to protect intellectual property
[3] Such as SolidWorks, CREO, CATIA, NX

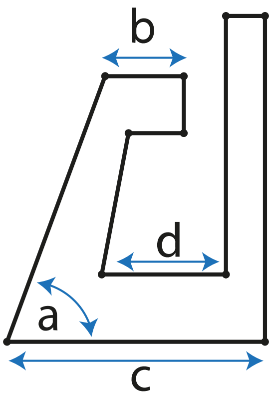


Figure 1: Original sketch with four variables; a, b, c, and d.

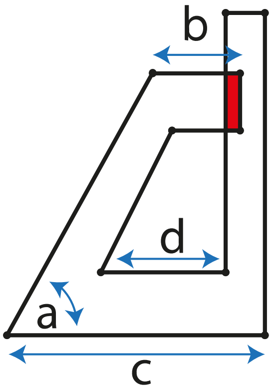


Figure 2: Sketch failure due to overlap (red) caused by a change of variable a.

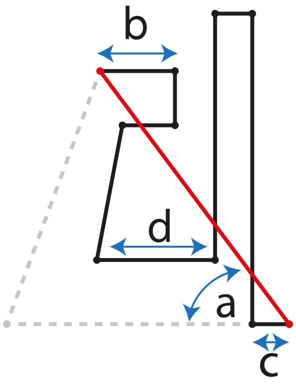


Figure 3: Sketch failure due to line flip (red) caused by major change of variable c.

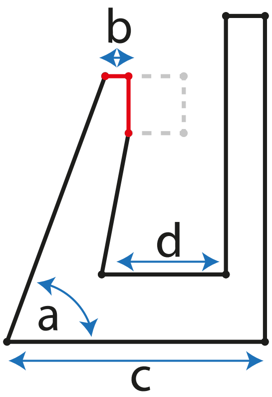


Figure 4: Design intent is lost due to incorrect line angle (red).

positions) and geometrical (coaxial, tangential, perpendicular, etc.), both of which can be used to achieve an iso-constrained sketch. In this paper, the primary focus is on the dimensional constraints where variation can be applied. However, a correctly iso-constrained sketch can become over-constrained or inconsistently constrained when variation is applied. An over-constrained sketch does not have a unique configuration, and inconsistent constraints can cause lines to flip, as seen in Fig. 3. Any of the two will cause the sketch to fail. It is worth mentioning that the flipping behavior can be software sensitive due to how the sketch line positions are determined during regeneration. How the recalculation is performed is typically proprietary knowledge of the software developers.

2.1.3 Failure Mode 3 - Incorrect Design Intent

The literature provides different ways to describe "design intent" [23, 18, 7], however ISO 10303-108 states it as "intentions of the designer of a model with regard to how it may be instantiated or modified". Therefore, correct design intent refers to the sketch's ability to maintain the form which fulfills the design objective and should be able to do so within the defined solution space. A simple example of incorrect design intent is shown in Fig. 4, where the change to dimension b has altered the structure's ability to receive a counter-part in the snap feature. The incorrect design intent is problematic to automated FEA or optimization as it will not trigger a failed sketch but instead cause wasteful simulation attempts or result in impracticable solutions. The issue is particularly critical for parameter exploration tasks where major dimensional changes are applied, while less prominent doing tolerance exploration.

2.2 Robustness Assessment

According to Amadori et al. [1] flexibility, robustness, and the size of the solution space are closely related. "Flexibility" is defined as the model's ability to achieve different configurations by geometrical change. "Robustness" measures errors or instabilities due to changes; high robustness equals a low number of failures in regenerating the model. "Solution space" defines the limits the parametric variables can change. Generally, it is desirable to achieve high flexibility and robustness for a wide-reaching solution space, as it allows for an automatic search for optimized designs. In this paper, the solution space is split between; (i) tolerance exploration is $\leq \pm 5\%$, and (ii) parameter exploration is $\geq \pm 5\%$ from the nominal dimension, to indicate which type of design optimization will be possible. Optimization within the parameter space is more extensive than in the tolerance space, enabling larger design improvements. The sketch robustness is measured by Eq. (1), where σ is the level of applied variation.

$$\begin{gathered}\text{Robustness}_\sigma[\%] = \frac{\text{Successful regenerations}_\sigma}{\text{Attempted regenerations}_\sigma} \times 100, \\ \sigma = [\pm 1\%, \pm 5\%, \pm 10\%, \pm 30\%, \pm 50\%, \pm 80\%]\end{gathered} \tag{1}$$

To generate the matrix of regeneration attempts at each level of σ, a 2-level Fractional Factorial design was used; $2^{16-9} = 128$ attempts at each level of σ. The Fractional Factorial design was selected as it comes in a standard format and spreads the number of regeneration attempts evenly at the edges of the solution space. The levels of σ were distributed between the tolerance and parameter exploration to explore when variation becomes an issue. The high fraction was selected due to efficiency and that the number is commonly used in FEA-based variation simulation. However, to check if the fraction affected the robustness score, a comparison with one participant's original sketch was performed. The check consisted of comparing the robustness measure between a lower fraction, $2^{16-5} = 2048$ regenerations, with the results of the 128 regenerations, at each magnitude of variation. The results show that the average error for the six levels of variation is less than 1.9%. Using 128 regenerations was therefore deemed sufficiently accurate for the study.

3 DEVELOPING THE ROBUST SKETCH PRINCIPLES (RSPs)

The primary goal of the new RSPs is to lower the occurrence of regeneration failures caused by the failure modes described in section 2.1 and, by this, increase sketch robustness. Secondly, a vital feature of the new principles is to minimize additional work for the engineer compared to existing sketch practice.

3.1 Development and Requirements

The principles originate from experience that has led to an understanding of common similarities that either allowed the sketches to perform robustly or caused the failure modes described in section 2.1. An essential learning is that constraining sketches and applying tolerances on production drawing should be kept as separate disciplines as they serve different purposes. Secondly, with the requirement of minimizing additional work, complex morphological constraints [1] such as creating equation- or script-based relations should be avoided. While the failure modes can be minimized with these techniques, the more complex constraints are inefficient and require; (i) manual configuration of all the equations/scripts by identifying the essential relations and creating the limits to avoid overlaps. The manual configuration generates more complexity and increases the workload. (ii) Introducing predefined relations between individual constraints limits the sketch flexibility. For example, an equation-based relation $A = 2 \times B$ minimizes the possible solution space as it locks the ratio between the two variables an automated optimization based on FEA cannot detect the intermediate solutions. Therefore, the new RSPs are based on techniques that avoid adding complexity and fixed relations.

3.2 The New RSPs

The new RSPs are described and illustrated in Table 1. The principles aim to guarantee that the topology remains unaltered while the geometry changes allow exploring design variants. However, the principles are not meant to force the user to ignore the design goal. For example, if an angle, parallel, or equation-based constraint is needed for a specific reason, it is not "illegal", but the user is advised to minimize their usage.

Principle I advocates only to use length dimensions and avoid angles to the maximum extent possible. Angles are commonly found in CAD sketches, and at first glance, using angles to constrain a sketch is convenient and seemingly provides design control. However, an angle control lines in two dimensions. Therefore, the impact of changing the angle can be difficult to predict and result in sketch failure modes I, II, and III (see section 2.1), especially in complex sketches. While it is possible to have a sketch working robustly with angles, it is highly dependent on the sketch complexity and how the other sketch constraints are defined. Therefore, if an angle is required for a known design feature, e.g., a snap interface, it is suggested first to generate the design with the predefined angle, then remove the angle and apply length dimensions, as this enables sketch principle II.

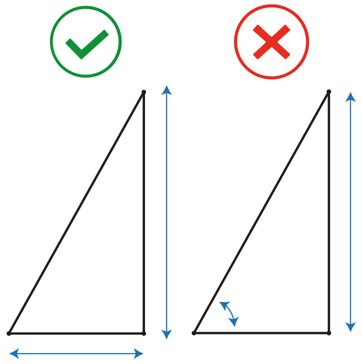
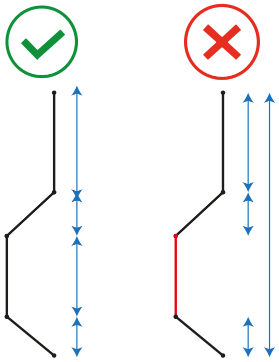
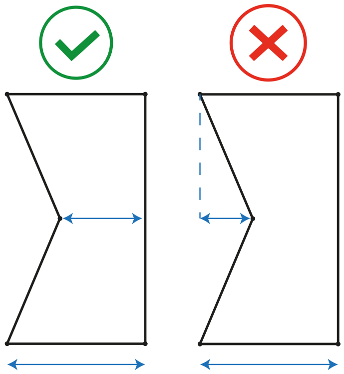
Principle II advocates for chaining of dimensions along the two sketch axes, either horizontal or vertical, see Table 1. Chaining enforces a simple overview of how the sketch is controlled, making it clear where active and passive constraints are located. An active constraint directly controls the sketch dimension. In contrast, a passive constraint adjusts as a function of the active constraints, i.e., acts as sacrificial lines to connect the structure; see the red line for principle II in Table 1. Thus, principle II ensures that as long as all chained constraints are positive, failure mode II is avoided as no sacrificial lines can be negative, even without the use of equation/script-based relations. However, principle II is knowingly in conflict with the practice of creating production drawings as the chaining leads to a massive build-up of tolerances. Application of principle II is therefore only valid in sketching and should be avoided on production drawings.

Principle III advocates for defining gaps and positive sketch areas, see Table 1. Applying gap control ensures a positive sketch area and avoids failure mode I, even when other constraints are varied. Thus, the direct measure minimizes the need to predict complex line behavior during the changes of multiple active constraints. Principle III forces the engineer to determine where material and gaps are required for functional performance, leading to increased control of the design intent (failure mode III).

4 METHOD TO EVALUATE THE RSPs

A comparative study was designed to measure the impact of the new RSPs, consisting of two experimental assignments given to two different groups of participants. The goal of each assignment was to iso-constraint a sketch that would allow for maximum sketch robustness. The starting point for both assignments is an under-constrained sketch. The sketch used in this case study is shown in Fig. 5, and the corresponding revolved feature is shown in Fig 6. The sketch is designed to have high complexity and challenge the cognitive ability of the participants. Generally, it is recommended to keep sketches simple and apply boolean operations to minimize complexity. However, the "good practice" is not strictly followed in the industry. Therefore, the sketch is purposely complex to challenge the participants to imagine how dimensional variation of unknown magnitude affects the sketch and apply constraints to minimize potential failure modes. The *size* of the sketch in scope requires 16 dimensional constraints before being iso-constrained. Additional and less quantifiable complexity is present by the internal gaps in the structure, generating multiple ways of overlapping. In the first assignment, the participants are instructed to add the remaining dimensional constraints and ensure maximum robustness when the sketch is subject to variation. Thus, the assignment serves as the baseline measurement for the achievable robustness based on the participant's experience with a time limit of 30 minutes. The 30 minutes was deemed sufficient to read the instruction and constraint the sketch without chancing their intuitive behavior. In the second assignment, the participants are introduced to the new RSPs (see Table 1) and asked to perform the same task all within a 30 minutes window, but without knowing the results of assignment 1. The intention of assignment 2 is to measure potential improvements in robustness by the new RSPs. For the complete participant material, see 7 and 7. A known bias is present by reusing the same sketch in both assignments. The reuse could potentially affect the result, as it is not possible to completely differentiate between the impact of RSPs and having practiced in assignment 1. Assignment 2 is therefore performed immediately after and without knowledge of assignment 1 results to minimize this effect. Due to the provided sketch file formats, the participants could perform the assignments in 3DX/CATIA or SOLIDWORKS. Assignments performed in SOLIDWORKS were afterward converted to 3DX/CATIA by the authors being careful to replicate the constraints exactly.

Table 1: The new Robust Sketch Principles for increasing robustness.

	Illustration	RSPs	Reasoning
Principle I		Only use length dimensions. Avoid using angles to the maximum extent possible.	A change to an angle can cause major changes to all parts of the sketch. The impact of the changes is often difficult to predict and, based on experience, is a significant contributor to sketch regeneration failures.
Principle II		Chain dimensions along the two sketch axes, either horizontal or vertical.	Chaining enforces a simple overview of how the sketch is controlled, making it clear where active and passive constraints are located. An active constraint directly controls the sketch dimension, while an passive constraint adjusts as a function of the active constraints, i.e., acts as sacrificial lines to connect the structure, see red line.
Principle III		Define required gaps and positive sketch areas to avoid overlaps.	Gap control ensures a positive sketch area even as other constraints are varied. Thus, the direct measure minimizes the need to predict complex line behavior during the change of multiple active constraints.

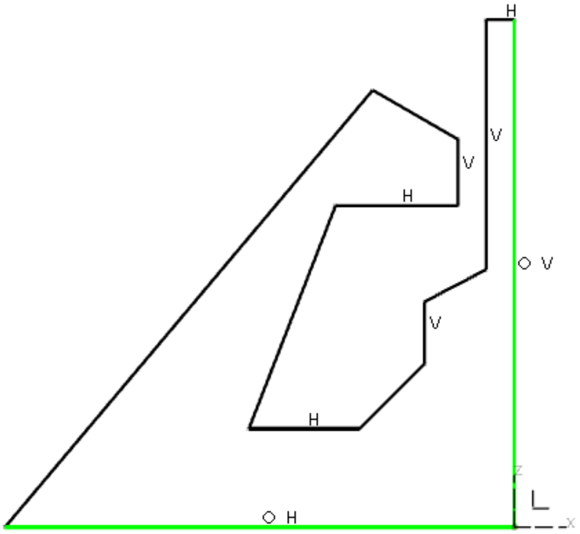


Figure 5: The provided sketch for assignments. Black lines = under-constrained, V = vertical constraint, H = horizontal constraint, O = coincident constraint to origin. The green lines indicate iso-constrained.

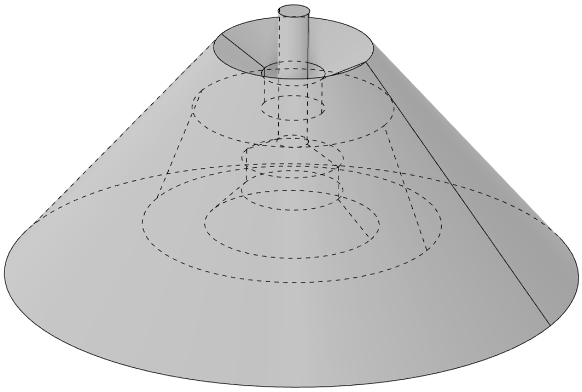


Figure 6: 3D representation of the revolved feature corresponding to the sketch for the assignments.

The study included two groups of participants. Group 1 consists of nine M.Sc. engineering graduate students from the Technical University of Denmark, all having completed basic and advanced CAD courses. Participants in group 1 performed the assignments in an uncontrolled environment in their spare time but independently. Assignment 2 was therefore received after assignment 1 was submitted to avoid participants prereading. Group 2 consists of five industrial CAD specialists with a minimum of 10 years of experience from a world-leading medical company. All five conducted the assignments individually within the same one-hour window. The aim of including two groups with different experience levels is to evaluate if experience affects the achievable robustness and whether the new RSPs affect the groups differently.

Following the completion of both assignments by all participants, data analysis was carried out. The Process Composer App in 3DX [13] was utilized to automate the process of applying dimensional variation with the 2-level Factional Factorial design. The process output was either "successful" or "failed" regeneration. Once all 21504[4] sketch configurations were performed, each participant's sketch's robustness measure was calculated at all six magnitudes of dimensional variation, defined in Eq. (1). It must be highlighted that applying variation as a percentage in combination with principles I and II affects how much the sketch is "stretched". As angles are removed and chaining applied, the nominal dimensions can be reduced, resulting in a possibly less "stretched" sketch. The effect of reduced nominal dimensions is confounded with the principle effects and not possible to separate out; however, it is expected to be less significant.

The data from the two assignments were used to test the following hypotheses and measure the statistical effect of the new RSPs. The hypotheses are shown in Eq. (2) and test if the average robustness of assignment 1 is equal to the average robustness of assignment 2 (H_0). If H_0 is rejected, the RSPs improve the sketch robustness, i.e., the robustness average of assignment 1 is not equal to the robustness average of assignment 2 (H_1). The statistical evaluation is based on Matched-paired t-tests with a confidence interval of 0.05 and the expected mean difference of zero. The method is selected as the data fulfills parried evaluation

[4] 14 participants, two sketches, 128 regenerations, six levels of variation.

of the participants before and after "treatment". The dependent variables are assumed continuous, the observations are independent of one another, the dependent variable is approximately normally distributed, and the dependent variable should not contain any outliers. The statistical test was performed in SAS JMP 15 [31].

$$\begin{aligned} H_0: &\quad \overline{R}_{i,\sigma} = \overline{R}_{i+1,\sigma} \\ H_1: &\quad \overline{R}_{i,\sigma} \neq \overline{R}_{i+1,\sigma} \\ \text{where} &\quad \overline{R} = \frac{\sum_{j=1}^{N} \text{Robustness}_{\sigma}[\%]}{N} \\ &\quad \text{i} = \text{assignment index} \\ &\quad \text{N} = \text{No. of participants} \end{aligned} \tag{2}$$

5 RESULTS OF COMPARISON

The results of the two sketch assignments are displayed in Fig. 7. The left column in the figure shows the robustness scores (Y-axis) without the principles applied (assignment 1) versus the magnitude of dimensional variation (X-axis). The right column shows the corresponding results with the RSPs applied (assignment 2). The first row compares the performance of the CAD specialists from industry, the middle row compares the engineering graduate students' performance, and the bottom row compares the averages of the two groups.

The robustness score without the RSPs shows that the industrial specialists achieve 100% robustness at $\pm 1\%$ dimensional variation. In contrast, some engineering graduate students cannot achieve 100% robustness even at this low magnitude of variation. At $\pm 5\%$ dimensional variation, the majority of participants cannot achieve 100% robustness, but there is a large spread in the robustness scores. The spread in performance is especially prominent for the engineering students, where one student (J) outperforms all others. In comparison, the student (L) drops to 21.9% robustness at $\pm 5\%$ variation and almost zero at larger magnitudes. At $\pm 10\%$ variation, only student (J) achieves 100% robustness, while all other participants continue to drop in robustness score. At $\pm 30\%$ and higher, the average robustness score for both groups is below 20% robustness, indicating severe issues if the sketch was used for automated parameter exploration studies and optimization [26]. A review of their sketches was conducted to gain further insight into the deviation in performance between student (L) and (J). It was found that the low robustness score of student (L) was related to the use of five angles and applying overlapping constraints, i.e., the opposite of chaining (Principle II). In contrast, student (J) unknowingly applied the basis of the new principles by avoiding angles in assignment 1 and, at the same time, already used some chaining and gap control. The results when RSPs are applied show a general improvement of all participants; see the right column in Fig. 7. One exception is participant N, who did not follow the principles by introducing angles in assignment 2. Consequently, participant N is removed from all following investigations for not obeying the RSPs in assignment 2. When applying the new RSPs, all participants achieve 100% robustness at $\pm 1\%$ variation. At $\pm 5\%$ variation, only two students cannot maintain 100% robustness, being (F and K), and they only perform marginally better from assignment 1. Although they had removed the angles, they did not apply chaining and gap control sufficiently. Instead, it looks like assignment 1 was copied, the angles removed, and replaced directly with length constraints, thereby not adjusting the full sketch. The remaining specialists and students perform similarly as the variation increases, while student (I) stands out. By reviewing the sketches with the new RSPs enforced, most participants used two or three constraints for gap control. In contrast, student (I) exceeded all others by meticulously attempting to ensure that overlaps cannot occur with six gap constraints. At $\pm 10\%$ variation, nine (almost 10) out of 13 participants can achieve 100% robustness, rather than 1 out of 13 in the case without RSPs. At $\pm 30\%$ variation, only student (I) achieves 100% robustness, and at $\pm 50\%$, even student (I) cannot succeed.

The bottom row of Fig. 7 shows the average performances' of the specialists and students. The averages visualize the groups' improvement of sketch robustness with the RSPs and explore whether the groups are

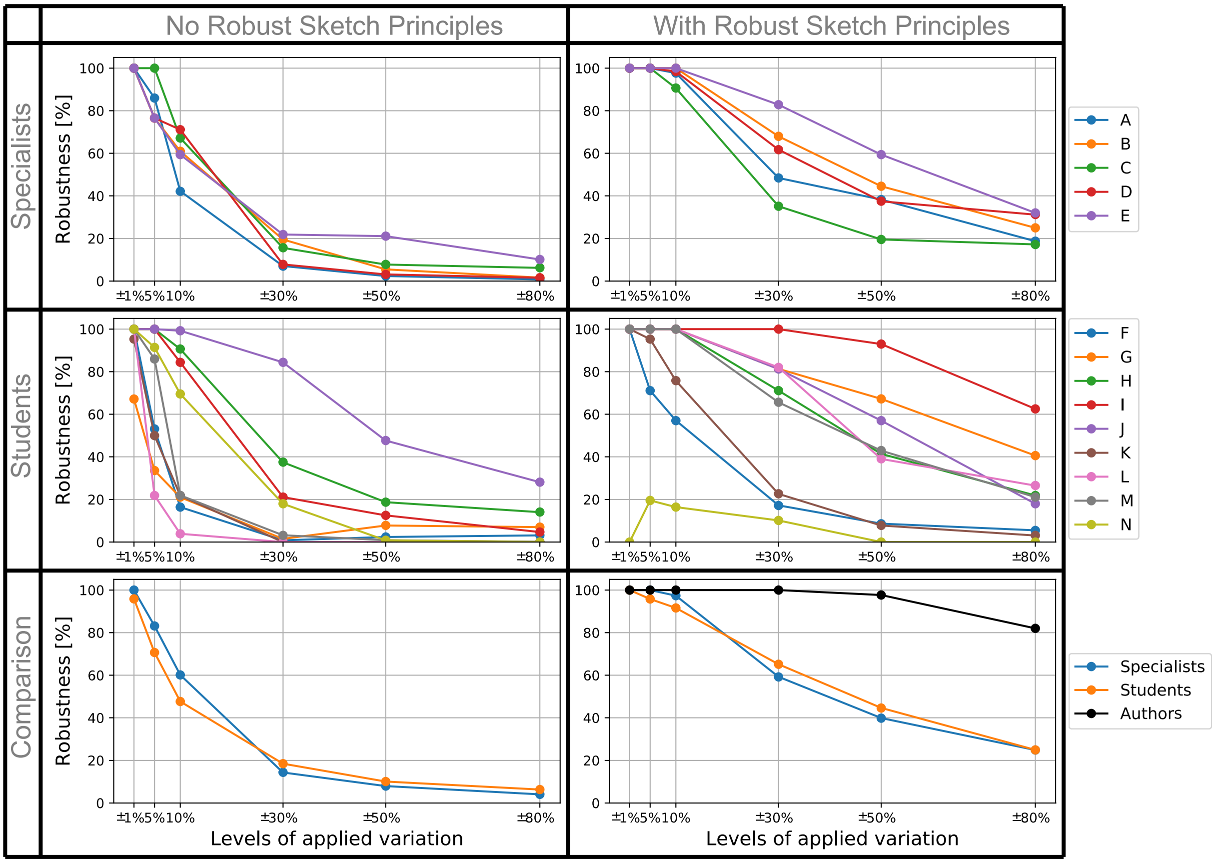


Figure 7: The assignment results of the two groups, with and without the RSPs. The results show an increase in robustness when the RSPs are applied for both groups.

affected differently. The shapes of the graphs are rather similar with and without applying the RSPs. Without the RSPs, the robustness deviations between the groups range from 1-10%, while the deviations are at 1-5% with RSPs. Furthermore, the specialist average marginally outperforms the students, with and without RSPs, in the range of ±1-10% variation, while it is opposite at ±30%. Thus, based on the averaged values, and despite the higher variation of student results, it is concluded that the RSPs affect students or specialists in a similar manner.

One possible source of bias in the results is that both groups completed assignment 1 first, followed by assignment 2. To avoid participants learning from assignment 1, in future studies, one group should complete assignment 1 and another group should complete assignment 2. Second, having more participants from various engineering sectors would improve the ability to generalize the results. The authors applied the RSPs to evaluate the relative performance of the participants to the greatest achievable robustness score. In this attempt, errors were investigated and used to adjust the constraints to minimize the number of regeneration failures. The results are shown as "Authors" in the bottom-left of Fig. 7, and the corresponding sketch constraints are shown in Fig. 8 with blue dimensional constraints indicating gap control. The improvements were achieved by mainly adjusting the gap control, including inspiration from the participants' sketches. The authors' attempt outperformed all participants and achieved 97.7% and 82% robustness at ±50% and ±80%

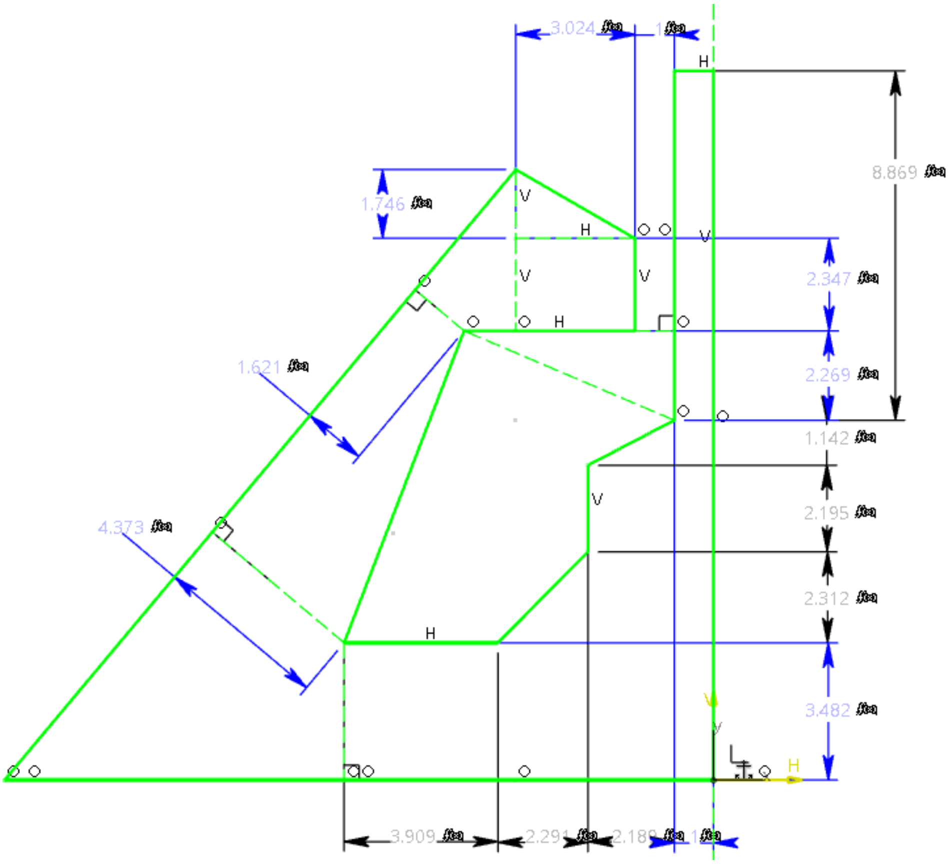


Figure 8: Corresponding author's attempt to maximize flexibility and robustness for the nominal sketch.

dimensional variation, respectively. The results indicate that the participants can further increase the robustness score with more training and practice. The statistical evaluation of the RSPs are presented in Table 2, while

Table 2: The results of the statistical analysis. The p-value (Prob > t) confirms that the RSPs improve the robustness with and above ±5% dimensional variation.

	±1%	**±5%**	**±10%**	**±30%**	**±50%**	**±80%**
Average without RSPs	97.11	73.86	50.78	16.94	9.97	5.96
Average with RSPs	100.00	97.41	93.80	62.86	42.79	24.89
Std error	2.51	9.03	7.97	7.50	6.00	4.72
Upper 95%	9.37	39.87	60.40	62.26	45.89	29.23
Lower 95%	-2.60	8.23	25.63	29.57	19.73	8.60
Prob > t	0.1372	0.0029	<.0001	<.0001	<.0001	0.0009
Prob < t	0.8628	0.9971	0.9999	1.0000	0.9999	0.9991

all participant data is shown in 7. The first two rows in Table 2 show the average robustness scores of all participants with and without the RSPs applied. The students and specialists are combined into one group as their average performances are almost identical, and separating them does not influence the conclusion of the results. At all levels of applied variation, the average robustness is the highest when applying the RSPs. Moreover, the RSPs are confirmed to statistically improve the sketch robustness for this assignment sketch and this group of participants, i.e., rejecting H_0 (see Eq. (2)), for all levels of variation except for $\pm 1\%$. The reason for this exception is that almost all participants achieved 100% robustness both with and without the RSPs. For all other levels of variation, the Prob > t value is lower than the alpha value of 0.005, the Std error is less than the average difference, and the confidence interval does not contain zero.

6 ENGINEERING APPLICATION AND RESULTS

The practical application of the RSPs is explored to demonstrate their efficiency in increasing sketch robustness in industry by considering three distinct sketches of existing designs.

The three industrial sketches[5] are shown in Table 3, with and without the new RSPs applied, and all sketches originate from the same company but were created by different engineers. The three sketches were selected as they have comparable complexity to the assignment sketch, requiring 15, 10, and 15-dimensional constraints, respectively, to be iso-constrained. The authors applied the RSPs without a time limit and with multiple iterations to circumvent regeneration failures. The robustness for the industrial sketches is tested with a Fractional Factorial design using 128 regeneration attempts, and the robustness score is again calculated with Eq. (1) at each level of variation. The industrial sketch robustness scores are shown in Fig. 9. At

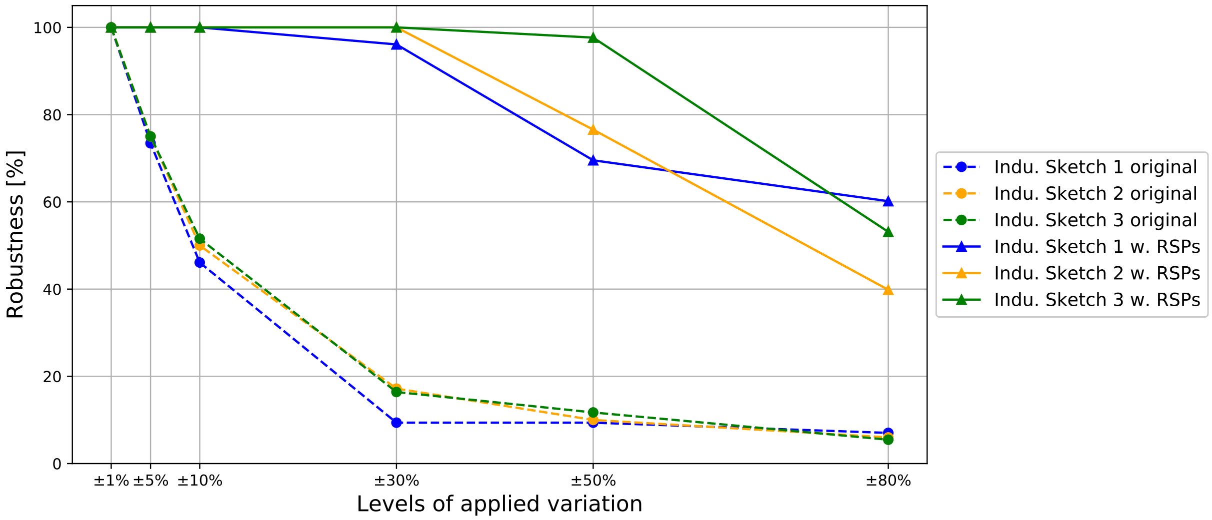
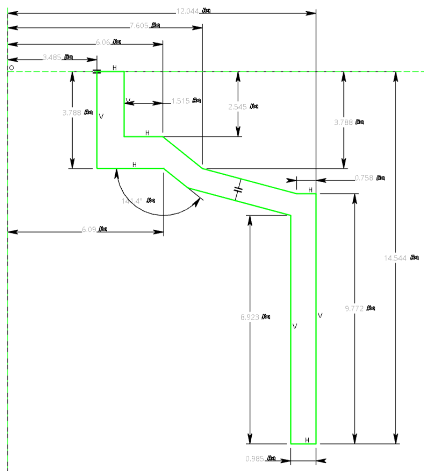
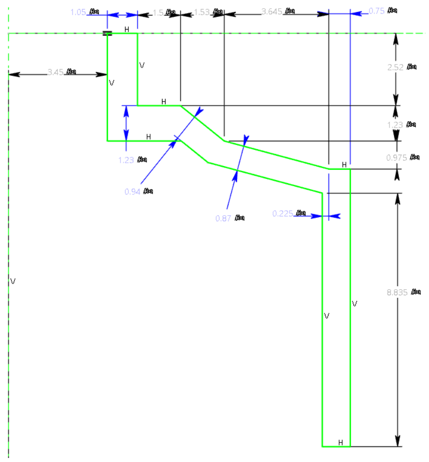
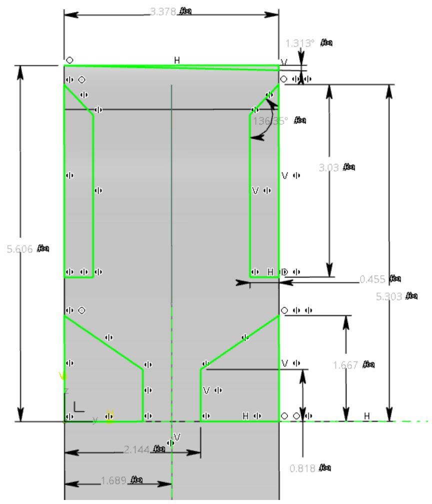
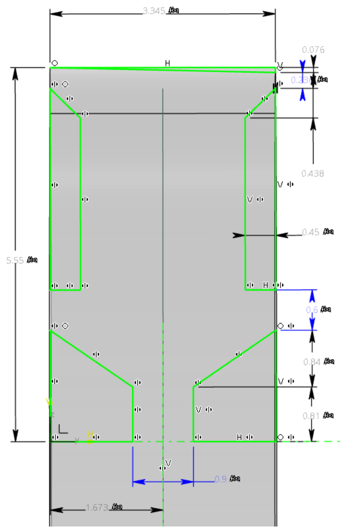
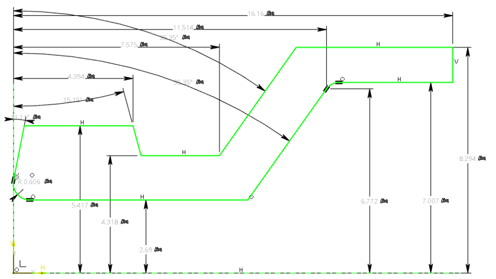
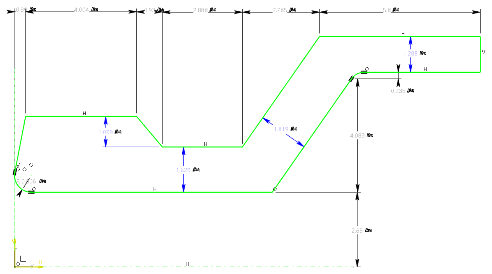


Figure 9: Robustness scores of the industrial sketches with and without the RSPs applied.

$\pm 1\%$ variation, the original sketch constraints are sufficient to achieve 100% robustness, but the robustness deteriorates as the variation increases to $\pm 5\%$ and more. In contrast, when applying the RSPs, the robustness of all three sketches increases substantially, and the regeneration failures start at $\pm 30\%$ variation. Moreover, it is worth noticing that the industrial sketches accomplish similar robustness scores compared to the group averages from the experimental assignments with and without RSPs (compare Fig. 9 to the bottom in Fig. 7). Figure 10 further illustrates the improvement in the robustness when applying the new RSPs. Here, showing a map of successful (green) and failed (red) regenerations for "Industrial sketch 3" with $\pm 30\%$ variation applied

[5]All sketch dimensions are modified to protect the intellectual property of the company.

Table 3: Comparison of constraints between original industrial sketches and with the new principles applied.

Original industrial sketches	**Industrial sketches with RSPs**
	
	
	

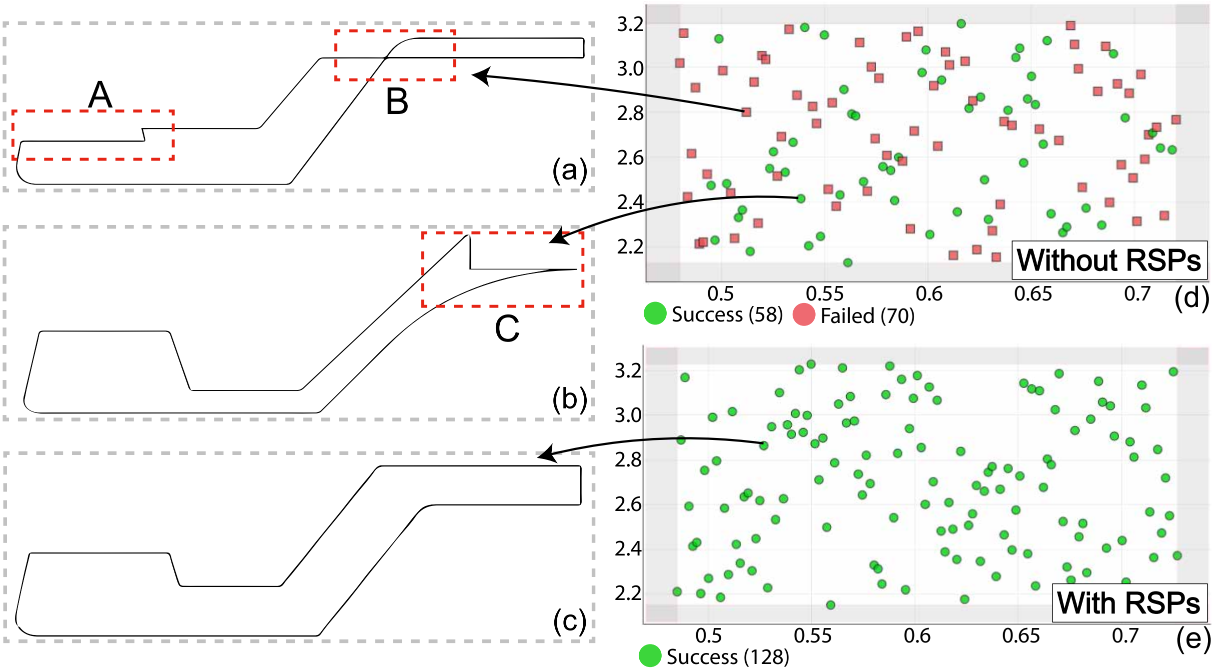


Figure 10: The figure shows the industrial sketch 3 with original constraints, affected by ±30% variation. The middle represents the solution space, where red and green indicate unsuccessful and successful regenerations, respectively. Left side shows an unsuccessful regeneration, where lines overlap and incorrect design intent is present.

with a Latin Hypercube design[6]. Figures 10d and 10e show two maps[7] of the solution space, with and without the RSPs applied, where the axes are dimensions of two sketch constraints. Several design configurations fail due to modes I, II, and III (see section 2), or a combination of the different modes when relying on the current practice (without the RSPs). In contrast, all markers are green in the corresponding map when applying the RSPs, meaning that all design configurations successfully regenerate (see Fig. 10e). As discussed, such successful regeneration is crucial when dealing with DOE methods that rely on few evaluations, exploring the solution space boundaries. For example, a fractional factorial design can benefit significantly from the new RSPs, and the effort spent on increasing sketch robustness is regained from the effort that otherwise is put into manually re-configuring the designs to avoid regenerations failures.

To exemplify the typical regeneration failures, Fig. 10a shows a regeneration that fails due to overlapping lines at point B (failure mode 1) together with a successful regeneration in Fig. 10c. The software detects the regeneration failure, and the design configuration is marked by red in the design map. However, the regeneration in Fig. 10a also has incorrect design intent (failure mode III), since the "neck feature" (at point A) is inverted (compared to Fig. 10c). Unfortunately, failure mode III is not automatically detected by the software. As illustrated by Fig. 10b, such software limitations can cause an incorrect design intent to pass successfully

[6]DOE type changed as the movies were created in 3DX/Parametric design study, which only enables Latin Hypercube design.
[7]Movies, showing how regeneration maps develop and all corresponding design configurations for the red and green markers, can be found here;

Video C: Industrial sketch 3, Original - URL: https://vimeo.com/567458911

Video D: Industrial sketch 3, with RSPs - URL: https://vimeo.com/567457371 (marked with green, see Fig.10d), which in turn influence subsequent DOE studies or optimizations. In fact, relying on regenerations with incorrect design intent can lead to unfortunate designs when combined with automated optimizations procedures. A fortunate side benefit of the new RSPs is that they limit incorrect design intents significantly. For the case in Fig. 10e, all regenerations showed correct design intent when applying the RSPs, ensuring valid structural behavior (see footnote 7).

7 CONCLUDING REMARKS

The present study underlines the need for improvements of robust sketch practice. Applying more than $\pm 1\%$ variation is likely to cause one or more of the sketch failure modes identified in Section 2.1, which complicates the use of FEA-based variation simulations to explore the solution space. The main contribution of this work is the new Robust Sketch Principles (RSPs) presented in Table 1 developed to increase sketch robustness. The study shows that engineers with very different expertise levels can achieve a statistically significant increase in sketch robustness by applying the RSPs after only 30 minutes of training. The findings of the study are essential for several reasons outlined below:

1. *The current sketch practice by the participating groups yields critically low robustness.* The consequence of the current sketch practice and limited sketch robustness is an inefficient design process, where resources are wasted on the manual re-configuring CAD sketches. Furthermore, sketch robustness is a critical barrier for FEA-based variation simulation, which requires an uninterrupted process flow of data between CAD, DOE, and FEA to be efficient. Based on the assignment results (see Section 5), dimensional variation in the tolerance range ($\pm$1-5%) is just within reach with the current practice, but it is not guaranteed. Therefore, it is unrealistic to perform parameter exploration ($\geq \pm 10\%$) and automated parametric optimization unless the participants incorporate an appropriate sketching practice like the new RSPs.

2. *Design experience does not improve sketch robustness; specific training does.* While experience usually increases performance (see [30, 5] focusing on feature structuring), the present study indicates no increase in sketch robustness with design experience. In contrast, the robustness seems to converge towards a critically low level, possibly due to a lack of focus on the topic or an acceptance of poorly modifiable CAD models (see Fig. 7).

3. *Production drawing and design sketching must be kept as separate disciplines.* An unfortunate consequence of experience with production drawings is the possible crossover effect into sketching. Production drawing dimensions applied to control tolerances are vital and a well-researched engineering topic, but the same techniques do not apply to sketches suitable for dimensional variation. The results from the assignments could indicate that some participants use the tolerance principles during sketching, and it has an unfortunate negative impact on the robustness. Thus one must clearly distinguish between CAD sketch constraints and dimensions applied to drawing indented for production. The present work outlines such new Robust Sketch Principles (see Table 1).

The goal should be to reach 100% robustness for any magnitude of dimensional variation to provide unlimited access to the solution space (e.g., for automated optimization). However, even the authors' attempts to apply the new RSPs to the assignment sketch did not reach 100% robustness for all levels of variation. Instead, the robustness starts decreasing at $\pm$50% variation, raising the questions: *What is the theoretical maximum variation possible while maintaining 100% robustness when all sketch dimensions are varied?*, which is a topic for future research. Although the number of participants and number of sketches is limited, a statistically significant increase in sketch robustness is demonstrated, indicating the value of the RSP. However, in scope for a future study is to include a broader range of participants and number/types of industrial sketches. The purpose is to evaluate and generalize the RSP's value across different engineering industries. Based on the current findings, a robust design process should be governed by: (i) Using Skeleton Modeling for assembly control, i.e., interfaces, gaps, and contacts between components, (ii) applying Resilient Modeling for controlling and creating a robust sequence of features, and (iii) adopting the new RSPs to maximize sketch robustness.

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Sketch constraint methodology experiment
Part 1

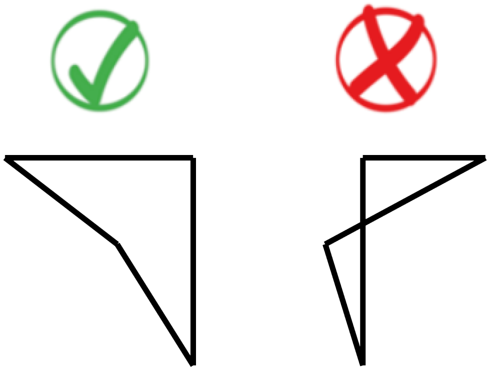

Figure 11: Only the sketch to the left is usable.

The image presented in Figure 12 is a sketch which forms the profile of a revolve feature revolved around the z-axis. It is unclear exactly what the dimensions of the sketch should be. Therefore, the sketch should be defined with as much flexibility as possible so it can be easily modified. If lines criss-cross after modification, the revolve feature will not be able to rebuild, illustrated in Figure 11. The sketch should therefore be constrained so criss-crossing is as unlikely as possible to happen for any dimension modification.

In SOLIDWORKS, CATIA or Creo. Make a copy of the attached sketch and rename it:
Part1_Firstname_Lastname

- Fully constrain the sketch to be maximally changeable (use lengths or angles). In Creo, use hard dimensions.
- Constrain the sketch so no lines will criss-cross
- **Do not change existing constraints**
- **You may not vary any dimensions to investigate robustness**

Please e-mail your result to: s052250@student.dtu.dk to receive part 2.

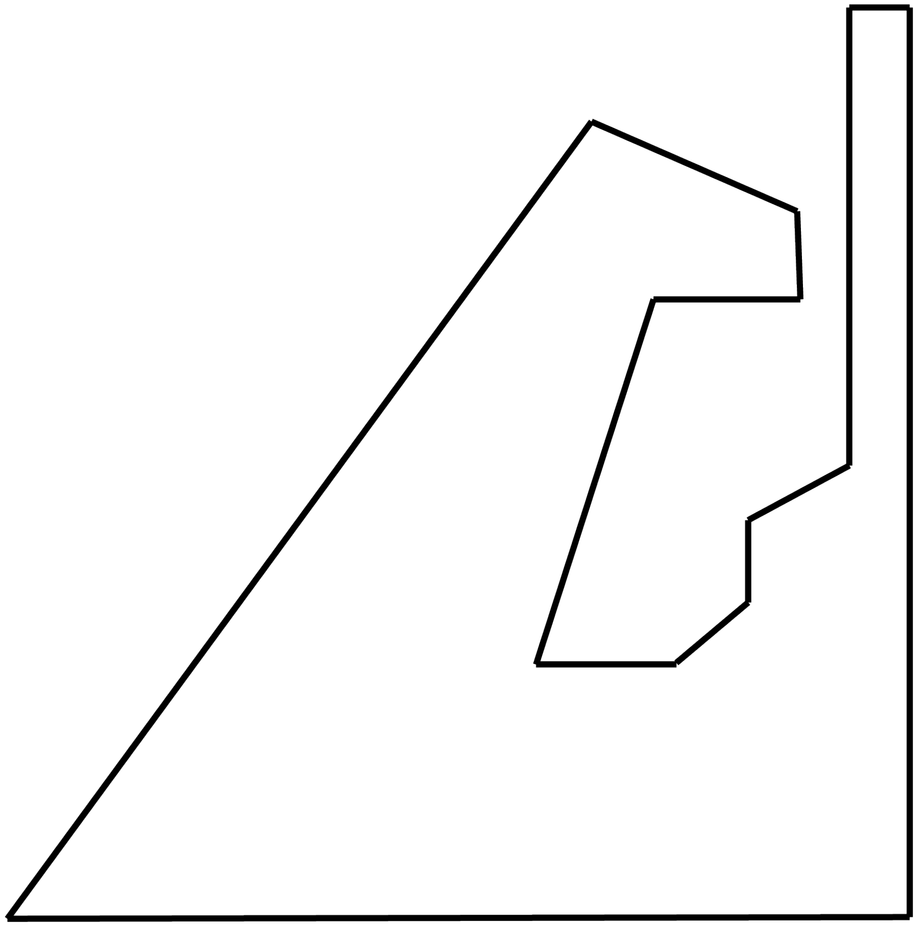

Figure 12: Sketch basic outline

Sketch constraint methodology experiment - Part 2

Introduction

The purpose of this experiment is to develop CAD that can be used for parametric optimisation and design exploration not production. When optimisation is carried out, the CAD model is changed and then its performance is analysed, usually with a FEA-simulation. If the CAD model fails to rebuild, the FEA-simulation will also fail, costing time and money. Robust CAD is therefore a crucial element in parametric FEA-based optimisation. This part will attempt to improve on the results from part 1 by introducing a method.

Implementation of a method

In SOLIDWORKS, CATIA or Creo. Make a copy of the attached sketch and rename it:

Part2_Firstname_Lastname

Part 1 is now repeated but with a few rules for constraining the sketch.

- Only lengths on lines may be used. Do not use point to line or point to point dimensions. In Creo, use hard dimensions.
- Length dimensions must be stacked along their respective axis (horizontal or vertical) as illustrated in Figure 13. When geometry is multilayered, create several lines of chaining as shown in Figure 16.
- When a chaining line is interrupted by a gap. Instead of assigning a distance between lines or points. Add a horizontal, vertical or perpendicular construction line between them and put a length dimension on it as shown in Figure 15.

For a short video example follow the link: https://youtu.be/kssRRk3utrE

CAD systems allow features, that are not unambiguously defined, to swap place, illustrated in Figure 14. When a sketch is rebuilt with a dimensional change, the program can in some cases swap the dimension which mostly ruins the sketch. Construction lines with lengths on them are more resistant to accidental swapping in CATIA, in which, the results of this test will be analysed. Construction geometry is explained in Section 7.

Please e-mail your result to: s052250@student.dtu.dk

Construction Geometry

A construction line is a regular sketching line which has been marked as "for construction" this means that it will not be used to generate any features, it is an invisible line used only to guide other geometry. Figure 17 shows how turn a line into construction geometry in SOLIDWORKS. Figure 18 shows how to do the same in Creo.

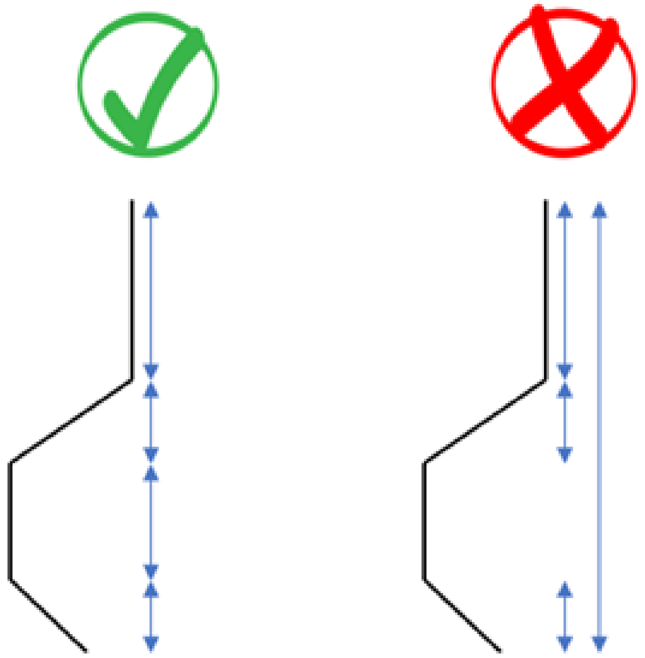

Figure 13: Chaining illustrated. The dimensions are stacked along the coordinate axis

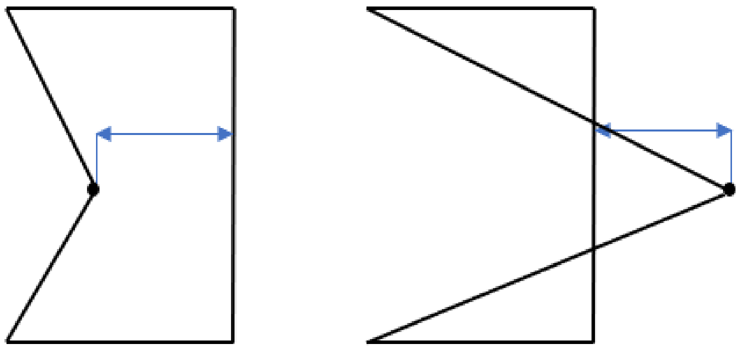

Figure 14: A distance between a point and a line. Both sketches are equally valid in a geometrical sense, but only the one to the left will rebuild the CAD feature made from it. The sketch on the right has lines that criss-cross and it will not rebuild

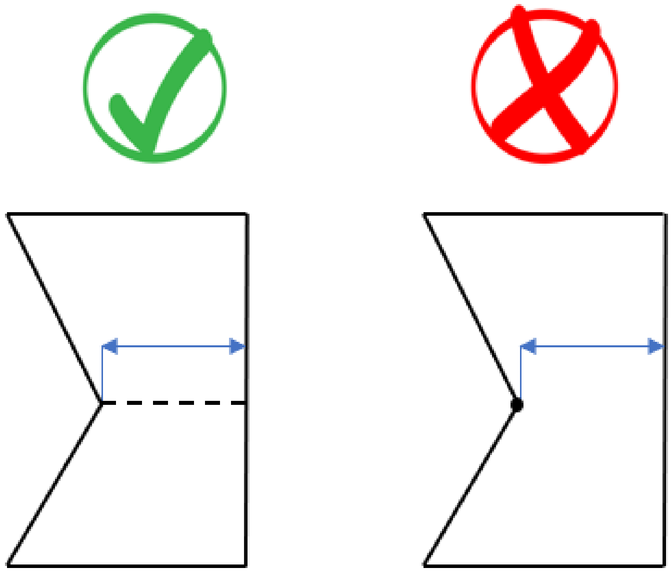

Figure 15: Replace dimensions with construction geometry (dashed line) where there are gaps that needs to be constrained

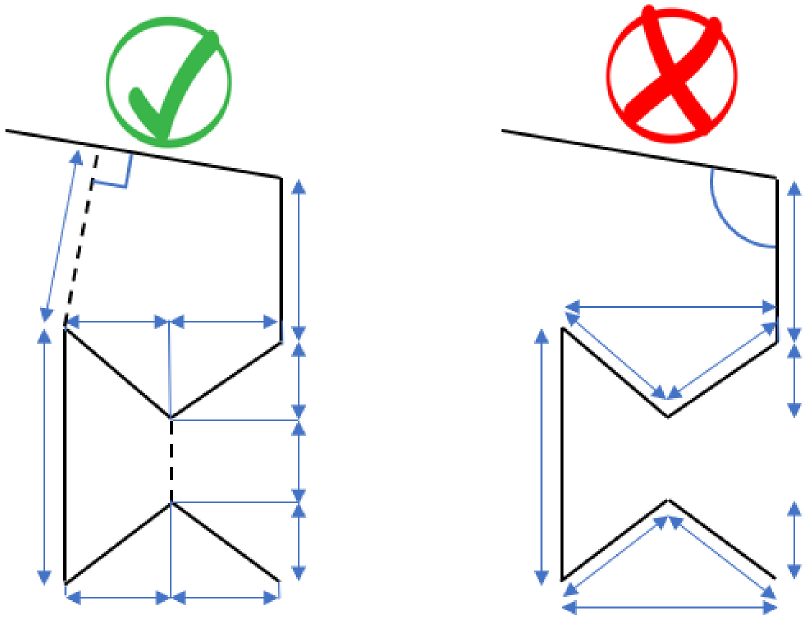

Figure 16: Create multiple lines of chaining to deal with multi layer geometry. Create construction lines (dashed lines) to fill gaps in the chaining lines

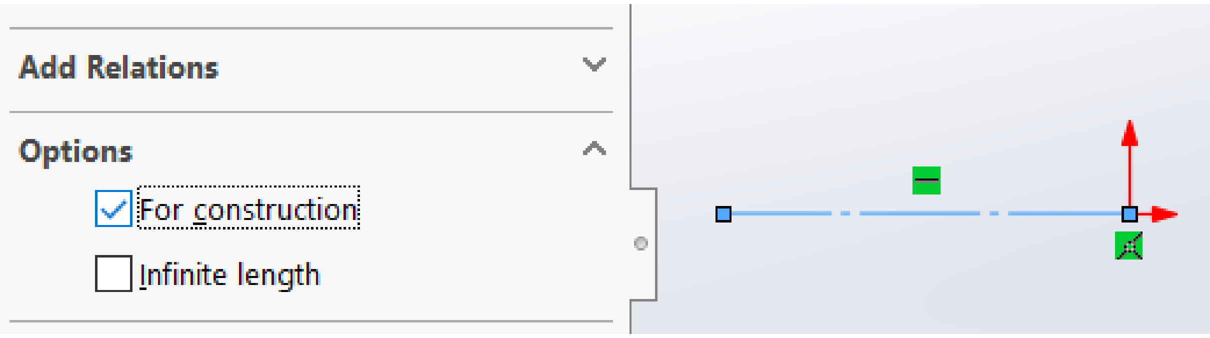

Figure 17: In SOLIDWORKS, click on the line, the option to make it a construction line appears in the menu to the left. The line will now not be used to generate any features

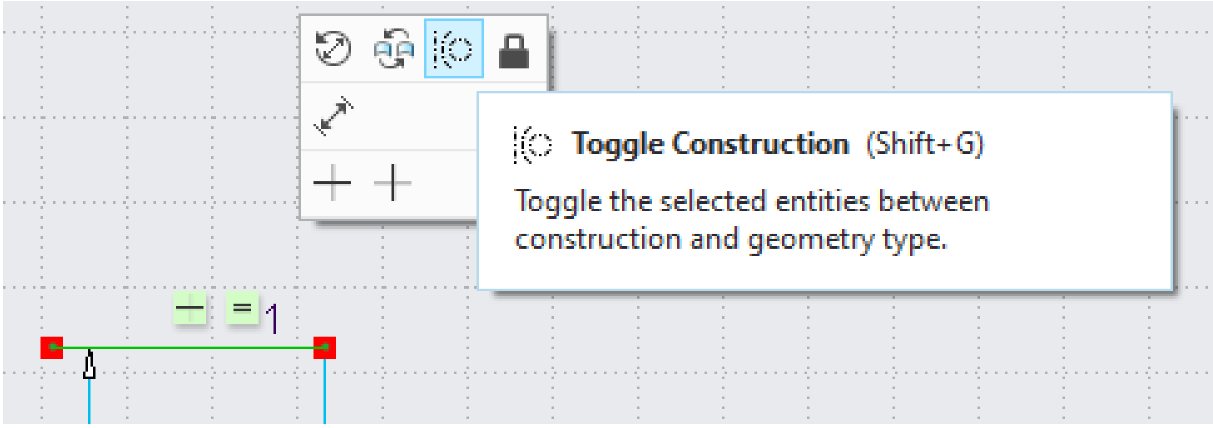

Figure 18: In Creo, click on the line, the option to make it a construction line appears in the popup menu. The line will now not be used to generate any features

Raw results of participant sketch assignment 1 and 2

Table 4: Robustness results from assignment 1, no principles applied.

Participants	±1%	±5%	±10%	±30%	±50%	±80%
A	100.0	85.9	42.2	7.0	2.3	0.8
B	100.0	76.6	60.9	19.5	5.5	1.6
C	100.0	100.0	67.2	15.6	7.8	6.3
D	100.0	76.6	71.1	7.8	3.1	1.6
E	100.0	76.6	59.4	21.9	21.1	10.2
F	100.0	53.1	16.4	0.8	2.3	3.1
G	67.2	33.6	21.1	1.6	7.8	7.0
H	100.0	100.0	90.6	37.5	18.8	14.1
I	100.0	100.0	84.4	21.1	12.5	4.7
J	100.0	100.0	99.2	84.4	47.7	28.1
K	95.3	50.0	21.9	0.0	0.0	0.0
L	100.0	21.9	3.9	0.0	0.0	0.0
M	100.0	85.9	21.9	3.1	0.8	0.0
~~N~~	~~100.0~~	~~91.4~~	~~69.5~~	~~18.0~~	~~0.8~~	~~0.0~~

Table 5: Robustness results from assignment 2, with RSPs applied.

Participants	±1%	±5%	±10%	±30%	±50%	±80%
A	100.0	100.0	97.7	48.4	38.3	18.8
B	100.0	100.0	100.0	68.0	44.5	25.0
C	100.0	100.0	90.6	35.2	19.5	17.2
D	100.0	100.0	98.4	61.7	37.5	31.3
E	100.0	100.0	100.0	82.8	59.4	32.0
F	100.0	71.1	57.0	17.2	8.6	5.5
G	100.0	100.0	100.0	81.3	67.2	40.6
H	100.0	100.0	100.0	71.1	41.4	21.9
I	100.0	100.0	100.0	100.0	93.0	62.5
J	100.0	100.0	100.0	81.3	57.0	18.0
K	100.0	95.3	75.8	22.7	7.8	3.1
L6	100.0	100.0	100.0	82.0	39.1	26.6
M	100.0	100.0	100.0	65.6	43.0	21.1
~~N~~	~~0.0~~	~~19.5~~	~~16.4~~	~~10.2~~	~~0.0~~	~~0.0~~